EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND U.S. LANDFALL STRIKE PROBABILITY FOR 2006

We continue to foresee another very active Atlantic basin tropical cyclone season in 2006. Landfall probabilities for the 2006 hurricane season are well above their long-period averages.

(as of 31 May 2006)

By Philip J. Klotzbach[1] and William M. Gray[2]

with special assistance from William Thorson[3]

This forecast as well as past forecasts and verifications are available via the World Wide Web at http://hurricane.atmos.colostate.edu/Forecasts

Emily Wilmsen and Brad Bohlander, Colorado State University Media Representatives, (970-491-6432) are available to answer various questions about this forecast

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ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2006

Forecast Parameter and 1950-2000 Climatology (in parentheses)	Issue Date 6 December 2005	Issue Date 4 April 2006	Issue Date 31 May 2006
Named Storms (NS) (9.6)	17	17	17
Named Storm Days (NSD) (49.1)	85	85	85
Hurricanes (H) (5.9)	9	9	9
Hurricane Days (HD) (24.5)	45	45	45
Intense Hurricanes (IH) (2.3)	5	5	5
Intense Hurricane Days (IHD) (5.0)	13	13	13
Net Tropical Cyclone Activity (NTC) (100%)	195	195	195

PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE LANDFALL ON EACH OF THE FOLLOWING COASTAL AREAS:

1) Entire U.S. coastline - 82% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 69% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 38% (average for last century is 30%)

4) Above-average major hurricane landfall risk in the Caribbean

Notice of Author Changes

By William Gray

The order of the authorship of these forecasts has been reversed from Gray and Klotzbach to Klotzbach and Gray. After 22 years (since 1984) of making these forecasts, it is appropriate that I step back and have Phil Klotzbach assume the primary responsibility for our project's seasonal, monthly and landfall probability forecasts. Phil has been a member of my research project for the last five years and has been second author on these forecasts for the last four years. I have greatly profited and enjoyed our close personal and working relationships.

Phil is now devoting more time to the improvement of these forecasts than I am. I am now giving more of my efforts to the global warming issue and in synthesizing my projects' many years of hurricane and typhoon studies.

Phil Klotzbach is an outstanding young scientist with a superb academic record. I have been amazed at how far he has come in his knowledge of hurricane prediction since joining my project five years ago. I foresee an outstanding future for him in the hurricane field. I expect he will make many new forecast innovations and skill improvements in the coming years. I plan to continue to be closely involved in the issuing of these forecasts for the next few years.

ABSTRACT

Information obtained through May 2006 continues to indicate that the 2006 Atlantic hurricane season will be much more active than the average 1950-2000 season. We estimate that 2006 will have about 9 hurricanes (average is 5.9), 17 named storms (average is 9.6), 85 named storm days (average is 49.1), 45 hurricane days (average is 24.5), 5 intense (Category 3-4-5) hurricanes (average is 2.3) and 13 intense hurricane days (average is 5.0). The probability of U.S. major hurricane landfall is estimated to be about 60 percent above the long-period average. Landfall probabilities are based upon our expectation for another very active season as well as analysis of our new steering current predictors for the East Coast and Gulf Coast of the United States.

We expect Atlantic basin Net Tropical Cyclone (NTC) activity in 2006 to be about 195 percent of the long-term average. This late May forecast is based on a newly devised extended range statistical forecast procedure which utilizes 52 years of past global reanalysis data. Analog predictors are also utilized. This 31 May forecast maintains our forecast from our early December 2005 and early April 2006 predictions as, although weak La Niña conditions have mostly returned to near neutral sea surface temperatures, conditions in the tropical Atlantic Ocean have become somewhat more favorable for an active hurricane season. Weaker trade winds have led to anomalous warming of the tropical Atlantic since the early part of April. We therefore continue to expect that another very active hurricane season is likely for the Atlantic basin.

Acknowledgment

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The second author gratefully acknowledges valuable input to his CSU research project over many years by former graduate students and now colleagues Chris Landsea, John Knaff and Eric Blake. We also thank Professors Paul Mielke and Ken Berry of Colorado State University for much statistical analysis and advice over many years.

DEFINITIONS

Atlantic Basin – The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño – (EN) A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3-7 years on average.

Hurricane – (H) A tropical cyclone with sustained low-level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day – (HD) A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.

Hurricane Destruction Potential – (HDP) A measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed (in 10^4 $knots^2$) for each 6-hour period of its existence.

Intense Hurricane - (IH) A hurricane which reaches sustained low-level winds of at least 111 mph (96 knots or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale (also termed a "major" hurricane).

Intense Hurricane Day – (IHD) Four 6-hour periods during which a hurricane has an intensity of Saffir/Simpson category 3 or higher.

Named Storm – (NS) A hurricane or a tropical storm.

Named Storm Day – (NSD) As in HD but for four 6-hour periods during which a tropical cyclone is observed (or is estimated) to have attained tropical storm intensity winds.

NTC – Net Tropical Cyclone Activity –Average seasonal percentage mean of NS, NSD, H, HD, IH, IHD. Gives overall indication of Atlantic basin seasonal hurricane activity.

ONR – Previous year October-November SLPA of subtropical Ridge in eastern Atlantic between 20-30°W.

QBO – Quasi-Biennial Oscillation – A stratospheric (16 to 35 km altitude) oscillation of equatorial east-west winds which vary with a period of about 26 to 30 months or roughly 2 years; typically blowing for 12-16 months from the east, then reversing and blowing 12-16 months from the west, then back to easterly again.

Saffir/Simpson (S-S) Category – A measurement scale ranging from 1 to 5 of hurricane wind and ocean surge intensity. One is a weak hurricane; whereas, five is the most intense hurricane.

SLPA – Sea Level Pressure Anomaly – The deviation of sea level pressure from observed long-term average conditions.

SOI – Southern Oscillation Index – A normalized measure of the surface pressure difference between Tahiti and Darwin.

SST(s) – Sea Surface Temperature(s)

SSTA(s) – Sea Surface Temperature(s) Anomalies

Tropical Cyclone – (TC) A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels; including hurricanes, tropical storms and other weaker rotating vortices.

Tropical Storm – (TS) A tropical cyclone with maximum sustained winds between 39 (18 ms^{-1} or 34 knots) and 73 (32 ms^{-1} or 63 knots) miles per hour.

ZWA – Zonal Wind Anomaly – A measure of the upper level (~200 mb) west to east wind strength. Positive anomaly values mean winds are stronger from the west or weaker from the east than normal.

1 knot = 1.15 miles per hour = 0.515 meters per second

1 Introduction

This is the 23rd year in which the CSU Tropical Meteorology Project has made forecasts of the upcoming season's Atlantic basin hurricane activity. Our research team has shown that a sizable portion of the year-to-year variability of Atlantic tropical cyclone (TC) activity can be hindcast with skill exceeding climatology. These forecasts are based on a statistical methodology derived from 56 years of past data and a separate study of analog years which have similar precursor circulation features to the current season. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our statistical analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be associated with the forthcoming seasonal Atlantic basin tropical cyclone activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

A variety of atmosphere-ocean conditions interact with each other to cause year-to-year and month-to-month hurricane variability. The interactive physical linkages between these many physical parameters and hurricane variability are complicated and cannot be well elucidated to the satisfaction of the typical forecaster making short range (1-5 days) predictions where changes in the momentum fields are the crucial factors. Seasonal and monthly forecasts, unfortunately, must deal with the much more complicated interaction of the energy-moisture fields with the momentum fields.

We find that there is a rather high (50-60 percent) degree of year-to-year hurricane forecast potential if one combines 4-5 semi-independent atmospheric-oceanic parameters together. The best predictors (out of a group of 4-5) do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain the portion of the variance of seasonal hurricane activity that is not associated with the other variables. It is possible for an important hurricane forecast parameter to show little direct relationship to a predictand by itself but to have an important influence when included with a set of 4-5 other predictors.

In a five-predictor empirical forecast model, the contribution of each predictor to the net forecast skill can only be determined by the separate elimination of each parameter from the full five predictor model while noting the hindcast skill degradation. When taken from the full set of predictors, one parameter may degrade the forecast skill by 25-30 percent, while another degrades the forecast skill by only 10-15 percent. An individual parameter that, through elimination from the forecast, degrades a forecast by as much as 25-30 percent may, in fact, by itself, show much less direct correlation with the predictand. A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 4-5 parameter forecast model. This is the nature of the seasonal or climate forecast problem where one is dealing with a very complicated atmospheric-oceanic system that is highly non-linear. There is a maze of changing physical linkages between the many variables. These linkages can undergo unknown changes from weekly to decadal time scales. It is impossible to understand how all these processes interact with each other. It follows that any seasonal or climate forecast scheme showing significant hindcast skill must be empirically derived. No one can completely understand the full complexity of the atmosphere-ocean system or develop a reliable scheme for forecasting the myriad non-linear interactions in the full-ocean atmosphere system.

2 Earlier 1 June Statistical Hurricane Forecast Scheme

Our original early June seasonal hurricane forecast scheme was developed in the early 1990s and demonstrated significant hindcast skill for the period of 1950-1991 (Gray et al. 1994). This scheme included measurements of West African rainfall as an important forecast input.

Since the observed shift of Atlantic Ocean SST patterns in 1995 [and the implied increase in the strength of the Atlantic Thermohaline Circulation (THC)], our original 1 June forecast scheme (1994) has consistently under-predicted Atlantic basin hurricane activity. Our earlier 1 June statistical scheme used West African rainfall data as an important predictor. We do not understand why, but the previously observed (1950-1994) strong association between West African rainfall and Atlantic hurricanes has not been reliable since 1994. We have lost confidence in the previous 1 June statistical forecast scheme compared to our newly developed one. We have thus decided to discontinue our earlier 1 June forecast scheme.

Over the past couple of years, we have been using an updated statistical scheme that utilized NOAA/NCEP reanalysis data. However, this scheme used mostly data from the previous fall and winter, and therefore we have recently developed a new early June (issued on 31 May) scheme that makes use of mostly spring data.

2.1 Newly-Developed 1 June Forecast Scheme

Our newly-developed early June forecast scheme also utilizes NOAA/NCEP reanalysis data and was developed on data from 1949-1989. It was then tested on independent data from 1990-2004 to insure that the forecast shows similar skill in this later forecast period.

The pool of four predictors for this new extended range forecast is given and defined in Table 1. The location of each of these new predictors is shown in Fig. 1. Strong statistical relationships can be extracted via combinations of these predictive parameters (which are available by the end of May), and quite skillful Atlantic basin hurricane forecasts for the following summer and fall can be made if the atmosphere and ocean continue to behave in the future as they have during the hindcast period of 1949-2004.

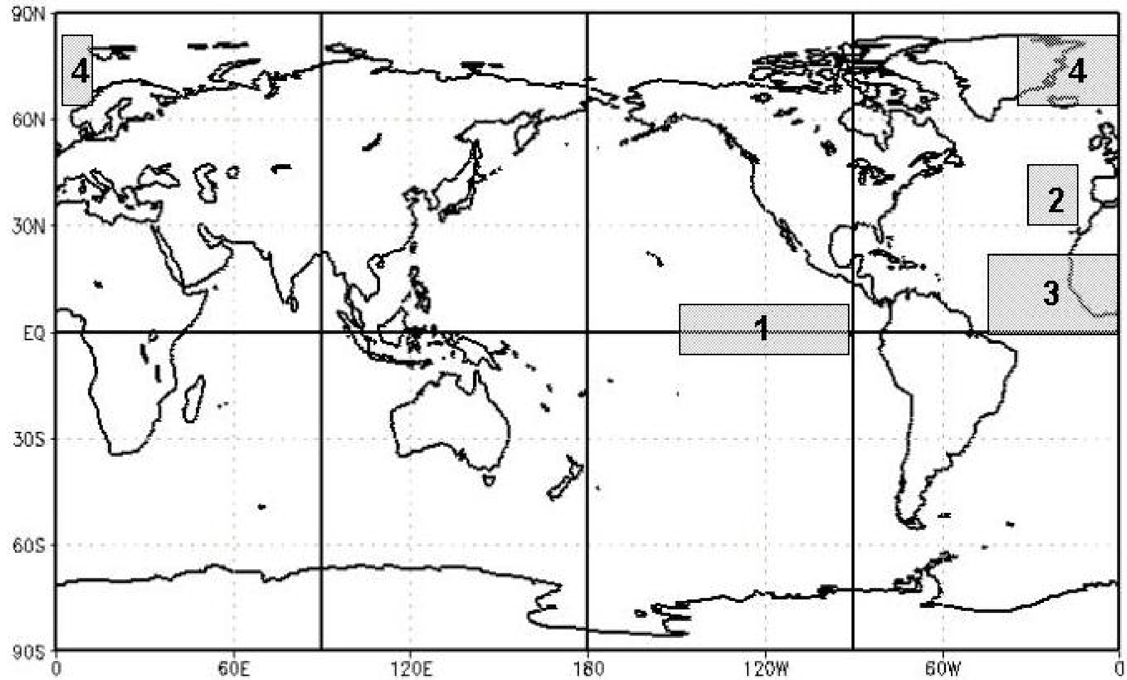

Figure 1: Location of predictors for the 31 May forecast for the 2006 hurricane season.

Table 1: Listing of 31 May 2006 predictors for this year's hurricane activity. A plus (+) means that positive values of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive values of the parameter indicate decreased hurricane activity this year. The combination of these four predictors calls for an above-average hurricane season.

Predictor	Values for 2006 Forecast
1) May SST (5°S-5°N, 90-150°W) (-)	+0.2 SD
2) April-May SST (30-45°N, 10-30°W) (+)	+0.5 SD
3) March-April SLP (0-20°N, 0-40°W) (-)	+0.2 SD
4) Previous November 500 MB Ht. (67.5-85°N, 50°W -10°E) (+)	+0.6 SD

Table 2 shows our statistical forecast for the 2006 hurricane season and the comparison of this forecast with climatology (average season between 1950-2000). Our statistical forecast is calling for above-average activity this year.

Table 2: 1 June statistical forecast for 2006.

Predictands and Climatology	Statistical Forecast Numbers
Named Storms (NS) – 9.6	11.0
Named Storm Days (NSD) – 49.1	57.4
Hurricanes (H) – 5.9	6.7
Hurricane Days (HD) – 24.5	28.8
Intense Hurricanes (IH) – 2.3	3.0
Intense Hurricane Days (IHD) – 5.0	7.7
Net Tropical Cyclone Activity (NTC) – 100	124

2.2 Physical Associations among Predictors Listed in Table 1

Brief descriptions of our 1 June predictors follow:

Predictor 1. May SST in the Eastern Equatorial Pacific (-)

(5°S-5°N, 90-150°W)

Sea surface temperatures in this area are taken to be a measure of ENSO conditions, as defined by the Nino 3 index. When sea surface temperatures are much cooler than normal, La Niña conditions are present, and when sea surface temperatures are much warmer than normal, El Niño conditions are occurring. Although there is some changeover during the summer and fall, in general, anomalies in this area tend to persist from the late spring through the summer and fall. El Niño conditions during the summer and fall tend to decrease Atlantic hurricane activity by increasing westerlies at upper levels across the Atlantic (Gray 1984a, Goldenberg and Shapiro 1996). These increased westerlies increase vertical wind shear across the area where Atlantic tropical cyclones develop.

Predictor 2. April-May SST off the Northwestern European Coast (+)

(30-45°N, 10-30°W)

Warm sea surface temperatures in this area indicate that the Atlantic subtropical ridge is weaker than normal, and therefore northeasterly trade winds across the Atlantic are also weaker than normal, and there is less cold water advection. These anomalies in April-May correlate strongly with a generally warm Atlantic Ocean as well as with low sea level pressure throughout the tropical Atlantic during the main part of the hurricane season from August-October. Weaker trade winds and easterly anomalies at upper levels (i.e., reduced vertical wind shear) during the summer/fall throughout the tropical Atlantic are also associated with this feature.

Predictor 3. March-April SLP in the Tropical Atlantic (-)

(0-20°N, 0-40°W)

Low sea level pressure in the tropical Atlantic during March-April implies increased instability, reduced trade wind strength and warm sea surface temperatures during the spring. In general, these are favorable conditions for tropical cyclone activity. Such conditions tend to persist through the summer and fall, as evidenced by strong lag correlations ($r > 0.4$) between this feature and warm sea surface temperatures in the tropical Atlantic during the late summer/early fall. Also, reduced vertical wind shear and continued low sea level pressure in the tropical Atlantic during the late summer/early fall are associated with low pressure in this area during March-April.

Predictor 4. Previous November 500 MB Geopotential Height in the far North Atlantic (+)

(67.5-85°N, 50°W-10°E)

Positive values of this predictor correlate very strongly ($r = -0.7$) with negative values of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). Negative AO and NAO values imply more ridging in the central Atlantic and likely also a warm North Atlantic Ocean (50-60°N, 10-50°W). Also, on decadal timescales, weaker zonal winds in the sub-polar areas are indicative of a relatively strong thermohaline circulation which is favorable for hurricane activity. Positive values of this November index are negatively correlated with both 200 mb zonal winds and trade winds the following August-October in the tropical Atlantic. The associated reduced tropospheric vertical wind shear enhances conditions for TC development. Other features that are directly correlated with this predictor are low sea level pressure in the Caribbean and a warm North and tropical Atlantic the following summer. Both of the latter are also hurricane-enhancing factors.

2.3 Hindcast Skill

Table 3 shows the degree of hindcast variance (r^2) explained by our new 1 June forecast scheme based on our 41-year developmental dataset (1949-1989), our skill on the independent dataset (1990-2004), and our skill over the entire dataset (1949-2004). Note that the scheme generally shows comparable or improved skill in the independent dataset, which lends increased confidence in its use.

Table 3: Variance (r^2) explained for our new 1 June forecast scheme in the developmental dataset (1949-1989), in the independent dataset (1990-2004), and over the entire dataset (1949-2004).

Variable	Variance (r^2) Explained Developmental Dataset (1949-1989)	Variance (r^2) Explained Independent Dataset (1990-2004)	Variance (r^2) Explained Entire Dataset (1949-2004)
NS	0.27	0.49	0.29
NSD	0.40	0.65	0.37
H	0.31	0.67	0.36
HD	0.51	0.63	0.49
IH	0.45	0.67	0.49
IHD	0.54	0.38	0.48
NTC	0.54	0.70	0.52

3 Analog-Based Predictors for 2006 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are substantially similar to 2006. These years also provide useful clues as to trends in activity that the upcoming 2006 hurricane season may bring. For this late May extended range forecast, we project atmospheric and oceanic conditions for August through October 2006 and determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current April-May 2006 conditions. Table 4 lists our analog selections.

We select prior hurricane seasons since 1949 which have similar atmospheric-oceanic conditions to those currently being experienced. Analog years for 2006 were selected primarily on how similar they are to conditions that are currently observed such as warm tropical and North Atlantic sea surface temperatures and neutral ENSO conditions. In addition, we look for analogs with similar conditions to what we project for August-October 2006 including warm Atlantic sea surface temperatures, neutral ENSO conditions and west phase QBO conditions.

There were four hurricane seasons since 1949 with characteristics similar to what we observed in April-May and what we project for August-October. The best analog years that we could find for the 2006 hurricane season are 1961, 1996, 2001 and 2004. We anticipate that 2006 will have comparable seasonal hurricane activity to what was experienced in the average of these four years. We believe that 2006 will be a very active season in the Atlantic basin.

Table 4: Best analog years for 2006 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	IH	IHD	NTC
1961	11	70.75	8	47.50	6	21.50	213
1996	13	79.00	9	45.00	6	13.00	192
2001	15	64.25	9	25.50	4	4.25	134
2004	14	90.25	9	45.50	6	22.25	229
Mean	13.3	76.1	8.8	40.9	5.5	15.3	192.0
2006 Forecast	**17**	**85**	**9**	**45**	**5**	**13**	**195**

4 ENSO

We believe that neutral ENSO conditions are likely to be present during August-October 2006. A weakening La Niña event was observed in the eastern and central tropical Pacific over the past few months. Sea surface temperatures have warmed somewhat over the past couple of months, and according to the Climate Prediction Center (CPC), neutral ENSO conditions are currently observed. However, Southern Oscillation Index (SOI) values remain positive, trade winds in the central Pacific have remained fairly strong, and oceanic heat content in the western and central Pacific is not particularly warm. We therefore do not expect El Niño conditions to develop this summer. In addition, most forecast models call for neutral ENSO conditions to persist for the next 4-6 months. When the tropical Atlantic is warm and neutral ENSO conditions are present, Atlantic basin hurricane activity is enhanced.

5 Adjusted 2006 Forecast

Table 5 shows our final adjusted late May forecast for the 2006 season which is a combination of our derived full 52-year statistical forecast, our analog forecast and qualitative adjustments for other factors not explicitly contained in either scheme. We foresee another very active Atlantic basin hurricane season. We anticipate that ENSO conditions will likely be neutral this summer and fall. Warm sea surface temperatures are likely in the tropical and North Atlantic during 2006, due to the fact that we are in a positive phase of the Atlantic Multidecadal Oscillation (AMO) (i.e., a strong phase of the Atlantic thermohaline circulation), and tropical Atlantic trade winds have been anomalously weak in April and May.

Table 5: Summary of our new late May statistical forecast, our analog forecast and our adjusted final forecast for the 2006 hurricane season.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	New Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (9.6)	11.0	13.3	17
Named Storm Days (49.1)	57.4	76.1	85
Hurricanes (5.9)	6.7	8.8	9
Hurricane Days (24.5)	28.8	40.9	45
Intense Hurricanes (2.3)	3.0	5.5	5
Intense Hurricane Days (5.0)	7.7	15.3	13
Net Tropical Cyclone Activity (100%)	124.0	192.0	195

6 Skill and Verification of 1 June Forecasts

We define forecast skill as the degree to which we are able to predict the variation of seasonal hurricane activity parameters above that specified by a long-term climatology. The latter is expressed as the ratio of our forecast error to the observed difference from climatology or:

Forecast Error / Seasonal Difference from Climatology

For example, if there were a year with five more tropical storms than average and we had predicted two more storms than average, we would give ourselves a skill score of 2 over 5 or 40 percent. By this measure, each of the seven parameters of our seasonal forecasts has shown some degree of skill from 1 June. Table 6 shows our skill based on 52 years of hindcasts from 1950-2001, and Table 7 displays our skill score in real-time forecasting for the last seven years. All parameters of our real-time forecasts have shown skill from 1 June.

Table 6: Average percent of variation explained of 1 June (or 31 May) hindcasts above that of climatology (in percent) for the 52-year period 1950-2001. A value of 30 means that we hindcast 30 percent of the variability from climatology or that we were unable to explain 70 percent of the variability from climatology.

Tropical Cyclone Parameter	Early June Hindcast Skill
NS	22
NSD	26
H	26
HD	32
IH	27
IHD	28
NTC	33

Table 7: Last seven years' (1999-2005) average percent of variation explained of our 'real-time' forecasts issued on 1 June (or 31 May) above that of climatology (in percent). A value of 40 means that we hindcast 40 percent of the variability from+ climatology or that we were unable to explain 60 percent of the variability from climatology.

Tropical Cyclone Parameter	Early June Forecast Skill
NS	49
NSD	53
H	38
HD	58
IH	38
IHD	27
NTC	47

Another way to consider the skill of our forecasts is to evaluate whether the forecast for each parameter successfully forecast above- or below-average activity. Table 8 displays how frequently our forecasts have been on the right side of climatology in hindcasts from 1950-2001 and in real-time forecasts for the past seven years (1999-2005). Note that our early June scheme has been successful at determining whether various hurricane parameters will be above- or below-average about 75% of the time at the extended lead time of 1 June (or 31 May) in hindcasts and over 90% of the time in real-time forecasts.

Table 8: The number of years that our tropical cyclone forecasts issued on 1 June (or 31 May) has correctly predicted above- or below-average activity for each predictand in (A) hindcast mode (1950-2001) and in (B) real-time forecast mode (1999-2005).

Tropical Cyclone Parameter	(A) Hindcast	(B) Forecast
NS	39/52	7/7
NSD	39/52	7/7
H	37/52	6/7
HD	35/52	6/7
IH	41/52	7/7
IHD	37/52	6/7
NTC	42/52	7/7
Total	270/364	46/49
Correct Prediction of Above or Below Climatology	**74%**	**94%**

Of course, there are significant amounts of unexplained variance in a number of the individual parameter forecasts. Even though the skill for some of these parameter forecasts is somewhat low, there is a great curiosity in having some objective measure as to how active the coming hurricane season is likely to be. Therefore, even a forecast that has shown only modest skill in past years should be considered worthwhile when the only other information available is climatology.

7 Landfall Probability

7.1 Introduction

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline. Whereas individual hurricane landfall events cannot be accurately forecast months in advance, the total seasonal probability of landfall can be forecast with statistical skill. With the observation that, statistically, landfall is a function of varying climate conditions, a probability specification has been developed through statistical analyses of all U.S. hurricane and named storm landfall events during the 20th century (1900-1999). Specific landfall probabilities can be given for all tropical cyclone intensity classes for a set of distinct U.S. coastal regions.

As shown in Table 9, NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage difference from the long-term average. Long-term statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of U.S. hurricane landfall. For example, landfall observations during the 20th century show that a greater number of intense hurricanes strike the United States coastline in years of above-average NTC.

Table 9: NTC activity in any year consists of the seasonal total of the following six parameters expressed in terms of their long-term averages. A season with 10 NS, 50 NSD, 6 H, 25 HD, 3 IH, and 5 IHD would then be the sum of the following ratios: 10/9.6 = 104, 50/49.1 = 102, 6/5.9 = 102, 25/24.5 = 102, 3/2.3 = 130, 5/5.0 = 100, divided by six, yielding an NTC of 107.

	1950-2000 Average	
1)	Named Storms (NS)	9.6
2)	Named Storm Days (NSD)	49.1
3)	Hurricanes (H)	5.9
4)	Hurricane Days (HD)	24.5
5)	Intense Hurricanes (IH)	2.3
6)	Intense Hurricane Days (IHD)	5.0

7.2 Steering Current Prediction

As mentioned in our early April forecast, we have considerably improved the statistical skill of our landfall probability forecasts through the inclusion of three predictors of mid-latitude steering flow for the Florida Peninsula and the East Coast and two predictors of mid-latitude steering flow for the Gulf Coast. Based on data from the NCEP/NCAR reanalysis, using a combination of our NTC forecast and the predictors listed in Tables 10 and 11 and displayed in Figures 2 and 3, we are able to hindcast approximately 30 percent of the variance in hurricane landfall for the Gulf Coast and approximately 50 percent of the variance in hurricane landfall for the Florida Peninsula and the East Coast over the period 1950-2004. As evidenced by hurricane landfall activity in 2004 and 2005 compared with the earlier period of 1995-2003, the strength of midlatitude westerly winds related to the position of the Bermuda High, is vitally important in determining how likely storms are to make landfall along either the East Coast or the Gulf Coast. The predictors listed in Tables 10 and 11 give us some degree of skill in predicting the mid-level steering flow during the hurricane season, and therefore add skill to our landfall probabilities beyond that specified by the combination of NTC and SSTA*. New research is finding that SSTA* does not add much additional skill beyond NTC and the steering current predictors, and therefore we have now discontinued the inclusion of SSTA* in our landfall probability calculations.

Table 10: Listing of 1 June steering current predictors for the East Coast and Florida Peninsula. The sign of the predictor associated with increased landfall is in parentheses.

Predictor	Values for 2006 Forecast
1) April-May 500 MB Ht. (35-50°N, 60-80°W) (+)	+0.1 SD
2) April-May SLP (20-40°S, 70-110°W) (+)	+0.2 SD
3) April-May 500 MB Ht. (70-85°N, 20°W-100°E) (+)	+1.9 SD

Table 11: Listing of 1 June steering current predictors for the Gulf Coast. The sign of the predictor associated with increased landfall is in parentheses.

Predictor	Values for 2006 Forecast
1) May 500 MB Ht. (10-25°S, 20-60°W) (+)	-0.8 SD
2) April-May 500 MB Ht. (40-55°S, 120°E-170°W) (+)	+0.1 SD

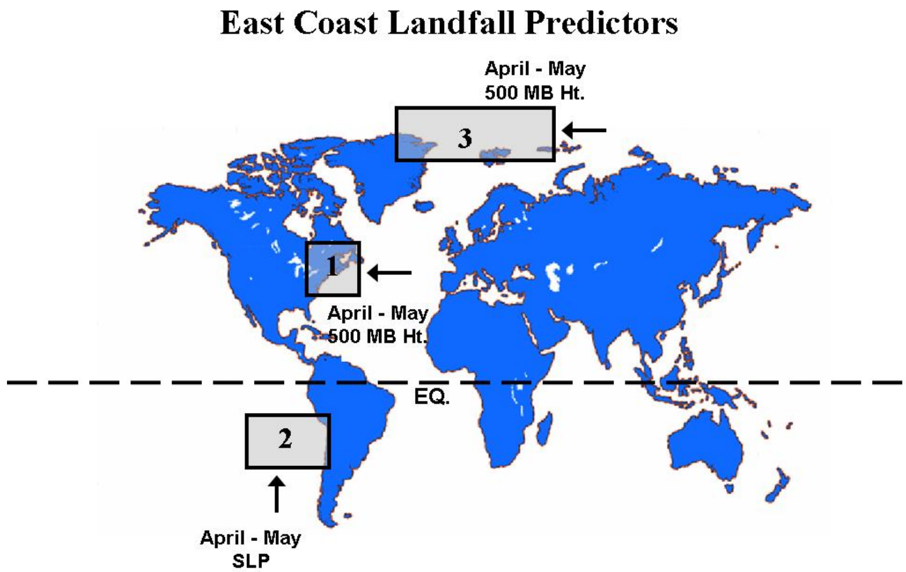

Figure 2: Listing of 1 June steering current predictors for the East Coast and Florida Peninsula.

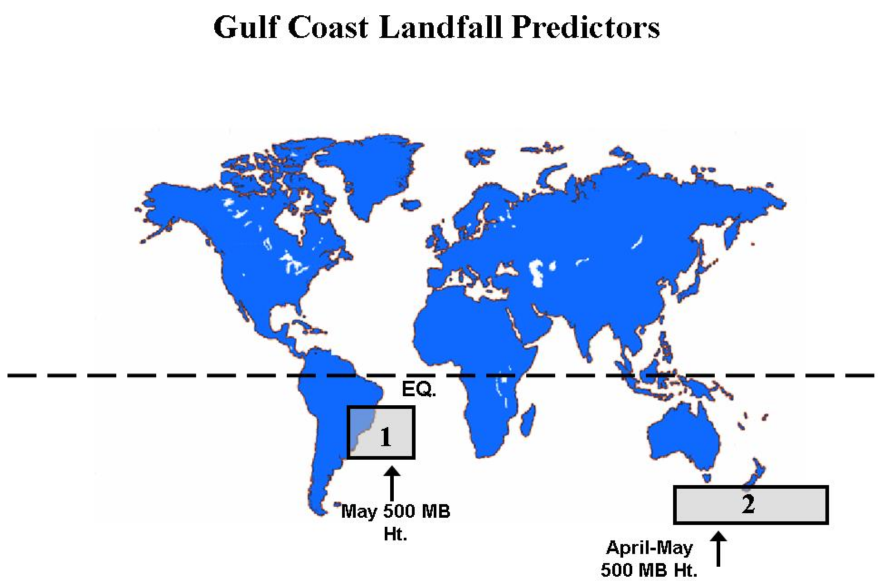

Figure 3: Listing of 1 June steering current predictors for the Gulf Coast.

7.3 Steering Current Predictor Physical Relationships

Brief descriptions of how we believe our April-May predictors relate to the steering currents likely to be present during the hurricane season are as follows:

East Coast Predictors:

Predictor 1. April-May 500 MB Geopotential Height in the Northeast United States and Canada (+)

(35-50°N, 60-80°W)

Anomalously high heights in the northeast United States during April-May, i.e., anomalous mid-level ridging, are associated with increased likelihood of hurricane landfalls along the East Coast and Florida Peninsula during the upcoming hurricane season. High heights in April-May tend to persist through August-October with an auto-correlation between the two periods of approximately 0.40. Easterly mid-level zonal wind anomalies associated with this anomalous ridging tend to drive tropical cyclones further west across the East Coast of the United States and inhibit early recurvature into the westerlies.

Predictor 2. April-May 500 MB Geopotential Height off the West Coast of South America (+)

(20-40°S, 70-110°W)

Anomalous ridging off the west coast of South America during April-May is commonly associated with strong equatorial east winds over the eastern Pacific and cold water upwelling. Such cold water upwelling is associated with a positive Southern Oscillation Index (SOI) and hence a La Niña event. La Niña events tend to persist from late May through the summer/fall period. In general, United States hurricane landfalls, especially in the Southeast, are more likely when the SOI is positive (Elsner 2003).

Predictor 3. April-May 500 MB Geopotential Height in the Arctic (+)

(70-85°N, 20°W-100°E)

Anomalously high heights in the Arctic are associated with a negative phase of the Arctic Oscillation (AO) (Thompson and Wallace 2000). A negative phase of the AO is associated with weaker westerlies across the North Atlantic. Stronger westerlies tend to steer storms away from the United States; whereas, weaker westerlies favor landfall along the East Coast of the United States (Xie et al. 2005).

Gulf Coast Predictors:

Predictor 1. May 500 MB Geopotential Height off the East Coast of South America (+)

(10-25°S, 20-60°W)

Anomalously high heights off the east coast of South America in May are strongly correlated with anomalous mid- and upper-level warming throughout the entire tropics during the spring. By the summer/fall period, a strong ridge develops over the southeastern United States with positive values of this predictor in May. This ridging tends to advect storms further west into the Gulf of Mexico and prevent early recurvature into the North Atlantic.

Predictor 2. April-May 500 MB Geopotential Height off the South Coast of New Zealand (+)

(40-55°S, 120°E-170°W)

Anomalous ridging off the south coast of New Zealand is associated with a positive value of the Antarctic Oscillation (AAO) (Thompson and Wallace 2000) and a stronger mid-latitude zonal circulation in the Southern Hemisphere. By August-October, when April-May values of this predictor are positive, La Niña conditions tend to be seen in the tropical Pacific, and there is also anomalous ridging seen over the southeastern United States. Anomalous ridging over the southeastern United States tends to enhance United States Gulf Coast landfall.

7.4 2006 Landfall Probabilities

Landfall probabilities for the 2006 season are calculated based upon values of the steering current predictors listed in the previous section and NTC. Landfall probabilities for the East Coast are quite high this year, due to a combination of both a very high predicted NTC value and favorable steering currents for East Coast landfall. In general, a negative North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) increases the likelihood of East Coast landfall, and both of these indices have been predominately negative so far this spring (Xie et al. 2005). Two of the three predictors utilized in our East Coast steering current model relate to the NAO and AO, especially Predictor 3, which as can be seen in Table 10, has very high values this year. The odds of a major hurricane making landfall along the East Coast are more than twice the climatological average value this year.

For the Gulf Coast, landfall probabilities are above the climatological average; however, they are not as high as those for the East Coast. Steering current parameters for the Gulf Coast are mixed, with one of the predictors being slightly positive and the other predictor being moderately negative. However, it is to be noted that Gulf Coast landfall probabilities are still above average (based on predicted high values of NTC), and therefore, coastal residents should prepare for a 38% probability of a landfalling major hurricane along the Gulf Coast.

Table 12 displays the landfall probabilities for the 2006 season.

Please visit our website at http://www.e-transit.org/hurricane for landfall probabilities for 11 U.S. coastal regions, 55 subregions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine.

Table 12: Estimated probability (expressed in percent) of one or more U.S. landfalling tropical storms (TS), category 1-2 hurricanes (HUR), category 3-4-5 hurricanes, and total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (Regions 1-4), and along the Florida Peninsula and the East Coast (Regions 5-11) for 2006. The long-term mean annual probability of one or more landfalling systems during the 20th century is given in parentheses.

Coastal Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	94% (80%)	90% (68%)	82% (52%)	95% (84%)	99% (97%)
Gulf Coast (Regions 1-4)	66% (59%)	44% (42%)	38% (30%)	62% (61%)	86% (83%)
Florida plus East Coast (Regions 5-11)	85% (51%)	83% (45%)	69% (31%)	87% (62%)	94% (81%)

8 Is Global Warming Responsible for the Large Upswing in 2004-2005 US Hurricane Landfalls?

8.1 Background

The U.S. landfall of major hurricanes Dennis, Katrina, Rita and Wilma in 2005 and the four Florida landfalling hurricanes of 2004 (Charley, Frances, Ivan and Jeanne) has raised questions about the possible role that global warming may be playing in these last two unusually destructive seasons.

The global warming arguments have been given much attention by many media references to recent papers claiming to show such a linkage. Despite the global warming of the sea surface of about 0.4°C that has taken place over the last two decades, global numbers of hurricanes and their intensity have not shown increases over the past twenty years (Klotzbach 2006). In addition, we have no valid physical theory as to why small changes of global average sea surface temperature (SST) should bring about increases in Atlantic basin hurricane activity. In the past century, Atlantic basin hurricane activity has been above-average both when global SST has been increasing (from the middle 1920s through the middle 1940s) and when global SST has been decreasing (from the middle 1940s through the middle 1960s).

The Atlantic has seen a very large increase in major hurricanes during the last 11-year period of 1995-2005 (average 4.0 per year) in comparison to the prior 25-year period of 1970-1994 (average 1.5 per year). This large increase in Atlantic major hurricanes is primarily a result of a multi-decadal increase in strength in the Atlantic Ocean thermohaline circulation (THC) which is not directly related to global temperature increase. Changes in ocean salinity are believed to be the driving mechanism. These multi-decadal changes have also been termed the Atlantic Multi-Decadal Oscillation

(AMO). It should also be noted that during this same time period, activity in the Northeast Pacific basin has decreased considerably. When activity in these two basins (the North Atlantic and the Northeast Pacific) is summed together, there has been virtually no trend in major hurricanes.

There have been similar past periods (1940s-1950s) when the Atlantic was just as active as in recent years. For instance, when we compare Atlantic basin hurricane numbers of the last 15 years with an earlier 15-year period (1950-1964), we see little difference in hurricane frequency or intensity even though global surface temperatures were cooler and there was a general global cooling during 1950-1964 as compared with global warming during 1990-2004.

8.2 Discussion

There is no physical basis for assuming that global hurricane intensity or frequency is necessarily related to global mean surface temperature changes of less than $\pm 0.5^{o}$C. As the ocean surface warms, global upper air temperatures warm as well to maintain conditionally unstable lapse-rates and global rainfall rates at their climatological values. Seasonal and monthly variations of sea surface temperature (SST) within individual storm basins show only very low correlations with monthly, seasonal, and yearly variations of hurricane activity (Shapiro and Goldenberg 1998, Klotzbach 2006). Other factors such as tropospheric vertical wind shear, surface pressure, low level vorticity, mid-level moisture, etc. play more dominant roles in explaining hurricane variability than do surface temperatures. Although there has been a general global warming over the last 30 years and particularly over the last 10 years, the SST increases in the individual tropical cyclone basins have been smaller than the overall global warming (about half) and, according to the observations, have not brought about any significant increases in global major tropical cyclones except for the Atlantic which, as has been discussed, has multi-decadal oscillations driven primarily by changes in Atlantic salinity. No credible observational evidence is currently available that directly associates global surface temperature change with changes in global hurricane frequency and intensity.

Most Southeast coastal residents probably do not know how fortunate they had been in the prior 38-year period (1966-2003) leading up to 2004-2005 when there were only 17 major hurricanes (0.45/year) that crossed the U.S. coastline. In the prior 40-year period of 1926-1965, there were 36 major hurricanes (0.90/year or twice as many) that made U.S. landfall. It is understandable that coastal residents were not prepared for the great upsurge in landfalling major hurricanes in 2004-2005. For many years, we had been warning that the southeastern United States should expect great increases in hurricane-spawned destruction in future years.

We should interpret the last two years of unusually large numbers of U.S. landfalling hurricanes as natural but very low probability years. During 1966-2003, U.S. hurricane landfall numbers were substantially below the long-term average. In the last two seasons, they have been much above the long-term average. Although the 2004 and

2005 hurricane seasons have had an unusually high number of major landfall events, the overall Atlantic basin hurricane activity has not been much more active than five of the recent hurricane seasons since 1995 (e.g., 1995-1996, 1998-1999, 2003). What has made the 2004-2005 seasons so unusually destructive is the higher percentage of major hurricanes that moved over the U.S. coastline. These landfall events were not primarily a function of the overall Atlantic basin net major hurricane numbers, but rather of the favorable broad-scale Atlantic upper-air steering currents which were present the last two seasons. It was these favorable Atlantic steering currents which caused so many of the major hurricanes which formed to come ashore.

It is rare to have two consecutive years with such a strong simultaneous combination of high amounts of major hurricane activity together with especially favorable steering flow currents. The historical records and the laws of statistics indicate that the probability of seeing another two consecutive hurricane seasons like 2004-2005 is very low. Even though we expect to see the current active period of Atlantic major hurricane activity continue for another 15-20 years, it is statistically unlikely that the coming 2006 and 2007 hurricane seasons, or the seasons which follow, will have the number of U.S. landfalling major hurricane events that we have seen in 2004-2005.

9 Forecast Theory and Cautionary Note

Our forecasts are based on the premise that those global oceanic and atmospheric conditions which preceded comparatively active or inactive hurricane seasons in the past provide meaningful information about similar trends in future seasons. It is important that the reader appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years. Moreover, these forecasts do not specifically predict where within the Atlantic basin these storms will strike. The probability of landfall for any one location along the coast is very low and reflects the fact that, in any one season, most U.S. coastal areas will not feel the effects of a hurricane no matter how active the individual season is. However, it must also be emphasized that a low landfall probability does not insure that hurricanes will not come ashore. Regardless of how active the 2006 hurricane season is, a finite probability always exists that one or more hurricanes may strike along the U.S. coastline or in the Caribbean and do much damage.

10 Forthcoming Updated Forecasts of 2006 Hurricane Activity

We will be issuing seasonal updates of our 2006 Atlantic basin hurricane forecasts on **Thursday 3 August**, **Friday 1 September** and **Tuesday 3 October 2006**. The 3 August, 1 September and 3 October forecasts will include separate forecasts and updates of August-only, September-only and October-only Atlantic basin tropical cyclone activity. A verification and discussion of all 2006 forecasts will be issued in late November 2006. Table 13 displays our forecast schedule for the remainder of the 2006 hurricane season. Our first seasonal hurricane forecast for the 2007 hurricane season will be issued in early December 2006. All of these forecasts will be made available on the web at: http://hurricane.atmos.colostate.edu/Forecasts.

Table 13: Timetable of upcoming forecasts and updates for the 2006 hurricane season.

Forecast Date	Based on Data Through	Upcoming Forecasts and Updates			
3 August 2006	July 2006	August Forecast	September Forecast	October Forecast	Updated Seasonal Forecast
1 September 2006	August 2006	August Verification	Updated September Forecast	Updated October Forecast	Updated Seasonal Forecast
3 October 2006	September 2006		September Verification	Updated October Forecast	Updated Seasonal Forecast
Late November 2006	Verification of all Forecasts				

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13 Verification of Previous Forecasts

Table 14: Summary verification of the authors' six previous years of seasonal forecasts for Atlantic TC activity between 2000-2005.

2000	8 Dec. 1999	Update 7 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	7	7	8	7	8
No. of Named Storms	11	11	12	11	14
No. of Hurricane Days	25	25	35	30	32
No. of Named Storm Days	55	55	65	55	66
Hurr. Destruction Potential	85	85	100	90	85
Intense Hurricanes	3	3	4	3	3
Intense Hurricane Days	6	6	8	6	5.25
Net Tropical Cyclone Activity	125	125	160	130	134

2001	7 Dec. 2000	Update 6 April	Update 7 June	Update 7 August	Obs.
No. of Hurricanes	5	6	7	7	9
No. of Named Storms	9	10	12	12	15
No. of Hurricane Days	20	25	30	30	27
No. of Named Storm Days	45	50	60	60	63
Hurr. Destruction Potential	65	65	75	75	71
Intense Hurricanes	2	2	3	3	4
Intense Hurricane Days	4	4	5	5	5
Net Tropical Cyclone Activity	90	100	120	120	142

2002	7 Dec. 2001	Update 5 April	Update 31 May	Update 7 August	Update 2 Sept.	Obs.
No. of Hurricanes	8	7	6	4	3	4
No. of Named Storms	13	12	11	9	8	12
No. of Hurricane Days	35	30	25	12	10	11
No. of Named Storm Days	70	65	55	35	25	54
Hurr. Destruction Potential	90	85	75	35	25	31
Intense Hurricanes	4	3	2	1	1	2
Intense Hurricane Days	7	6	5	2	2	2.5
Net Tropical Cyclone Activity	140	125	100	60	45	80

2003	6 Dec. 2002	Update 4 April	Update 30 May	Update 6 August	Update 3 Sept.	Update 2 Oct.	Obs.
No. of Hurricanes	8	8	8	8	7	8	7
No. of Named Storms	12	12	14	14	14	14	14
No. of Hurricane Days	35	35	35	25	25	35	32
No. of Named Storm Days	65	65	70	60	55	70	71
Hurr. Destruction Potential	100	100	100	80	80	125	129
Intense Hurricanes	3	3	3	3	3	2	3
Intense Hurricane Days	8	8	8	5	9	15	17
Net Tropical Cyclone Activity	140	140	145	120	130	155	173

2004	5 Dec. 2003	Update 2 April	Update 28 May	Update 6 August	Update 3 Sept.	Update 1 Oct.	Obs.
No. of Hurricanes	7	8	8	7	8	9	9
No. of Named Storms	13	14	14	13	16	15	14
No. of Hurricane Days	30	35	35	30	40	52	46
No. of Named Storm Days	55	60	60	55	70	96	90
Intense Hurricanes	3	3	3	3	5	6	6
Intense Hurricane Days	6	8	8	6	15	23	22
Net Tropical Cyclone Activity	125	145	145	125	185	240	229

2005	3 Dec. 2004	Update 1 April	Update 31 May	Update 5 August	Update 2 Sept.	Update 3 Oct.	Obs.
No. of Hurricanes	6	7	8	10	10	11	15
No. of Named Storms	11	13	15	20	20	20	27
No. of Hurricane Days	25	35	45	55	45	40	51
No. of Named Storm Days	55	65	75	95	95	100	125
Intense Hurricanes	3	3	4	6	6	6	7
Intense Hurricane Days	6	7	11	18	15	13	16.75
Net Tropical Cyclone Activity	115	135	170	235	220	215	275